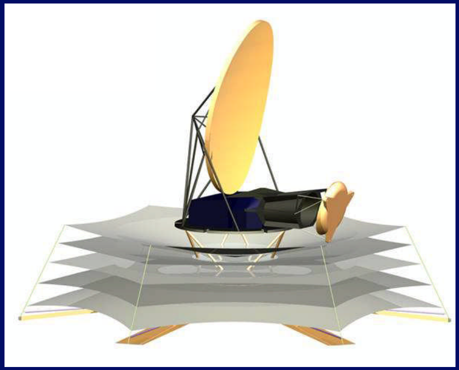
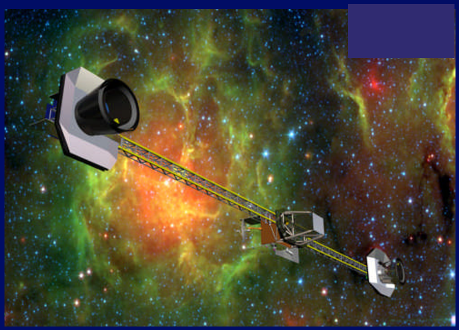
Extragalactic Sciences with the Far-Infrared Surveyor





Asantha Cooray

Outline

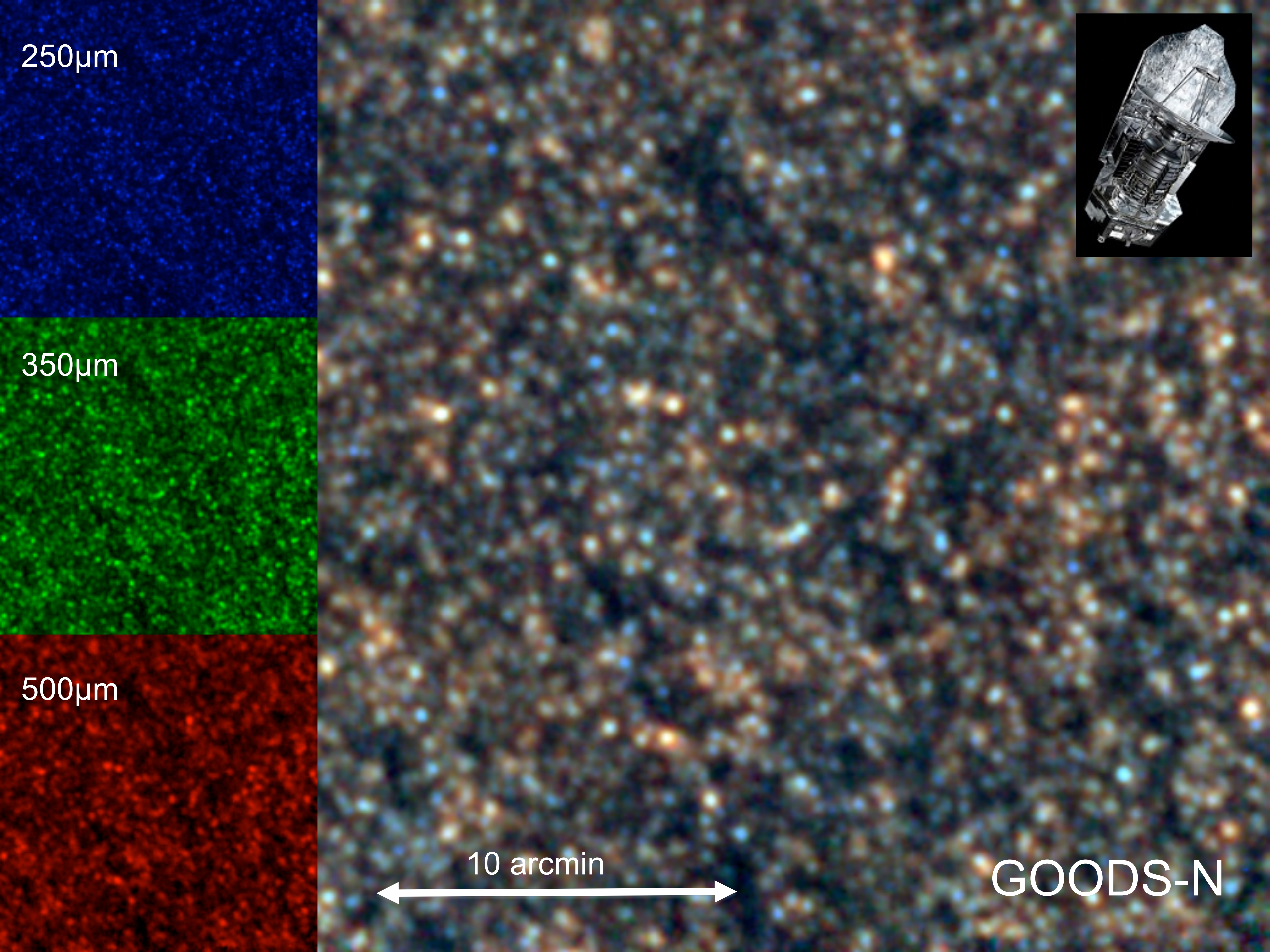
Quick summary of some key extragalactic astrophysics results from the Herschel Space Observatory

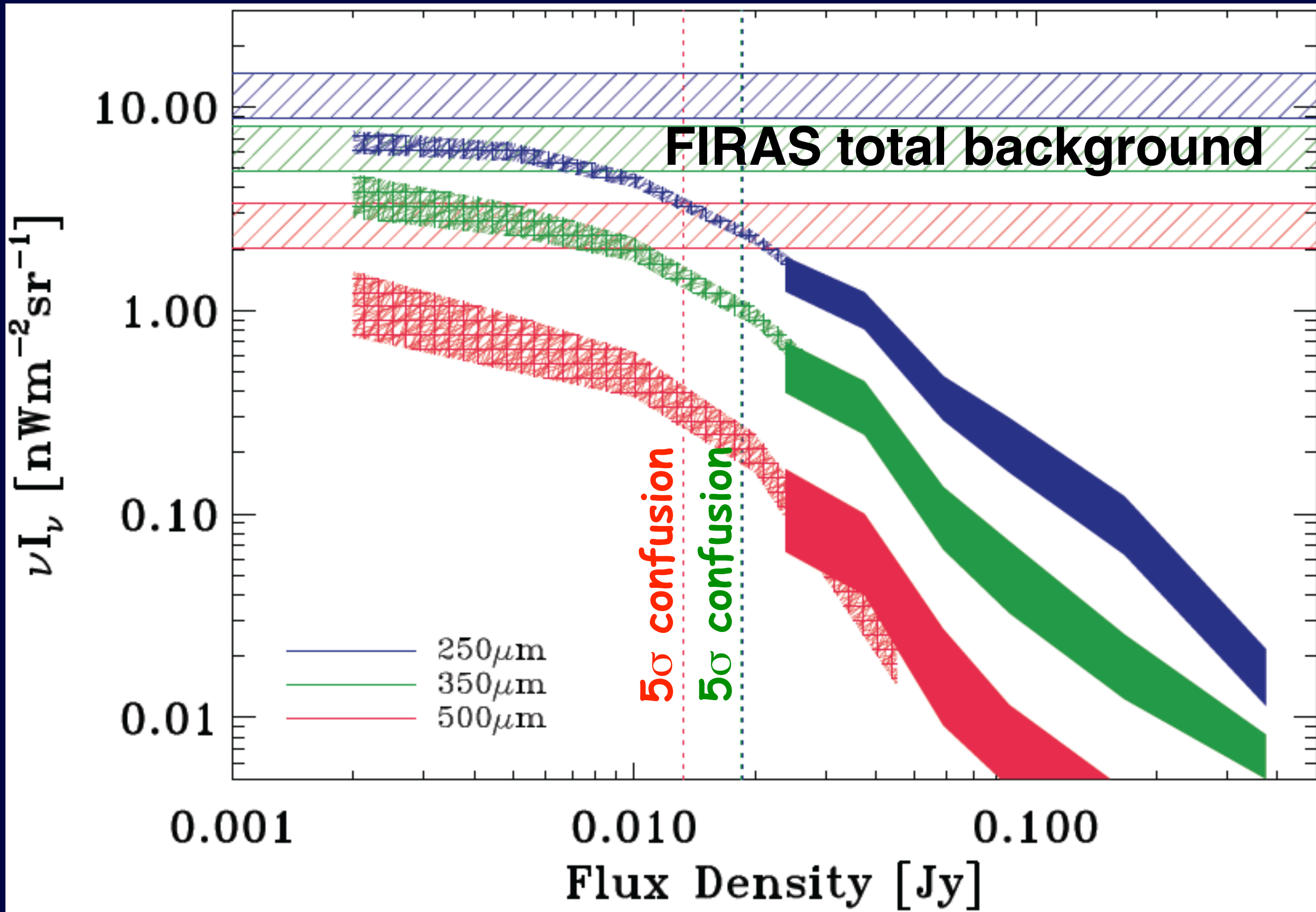
Science opportunities with Far-IR Surveyor
(single aperture and an interferometer)

New things:
(I) 3D spectral line intensity mapping

(II) Far-infrared probes of reionization
(especially molecular Hydrogen $10 < z < \sim 15$)

review of dusty star-forming galaxies Casey, Narayanan, Cooray 2014 Physics Reports

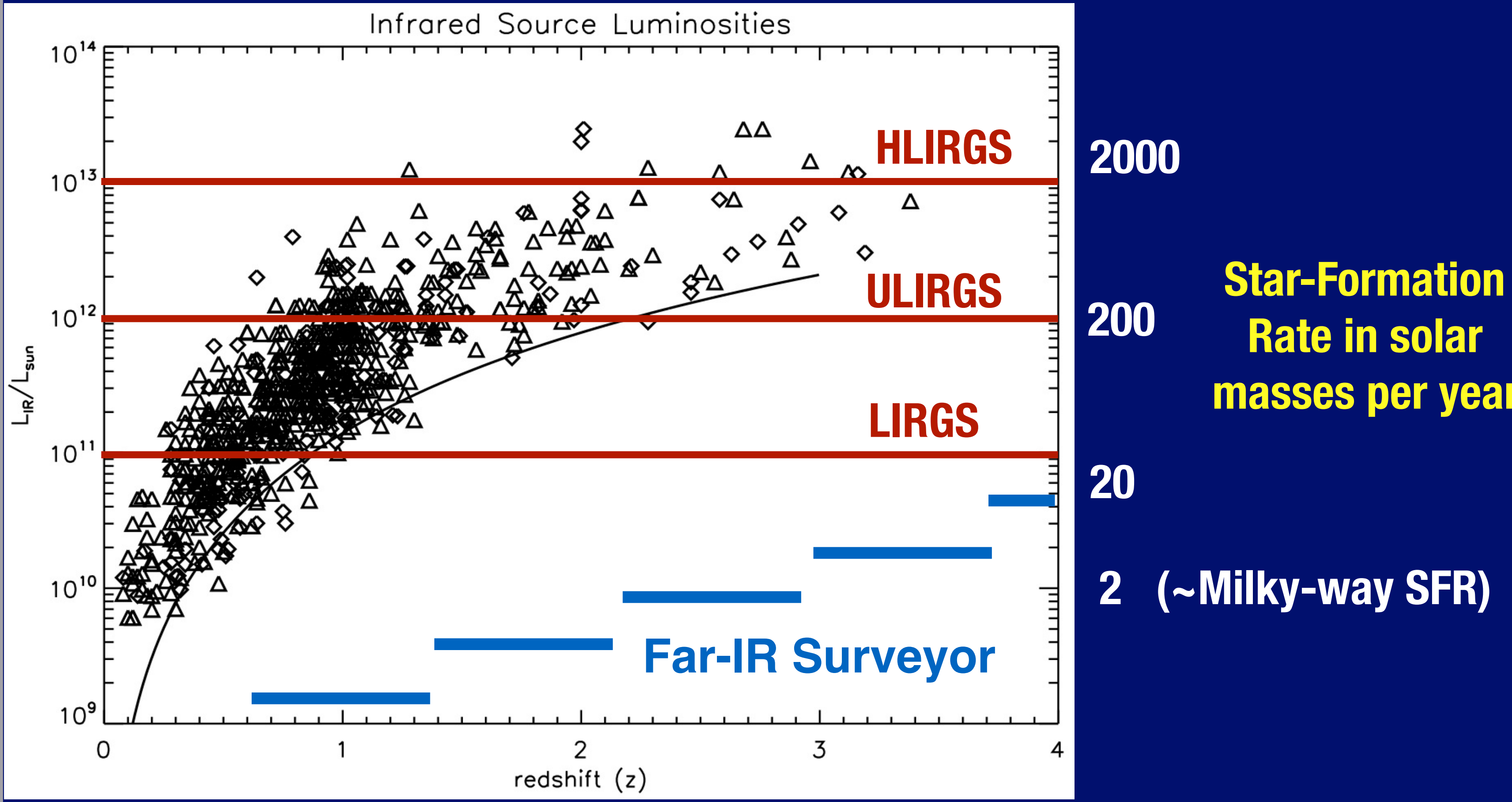

250μm
350μm
500μm
10 arcmin
GOODS-N



- **Source Counts**
  250, 350, 500 μm
  15%, 10%, 6%
- **P(D)**
  250, 350, 500 μm
  65%, 60%, 45%
- **Stacking:**
  250, 350, 500 μm
  80%, 80%, 85%

Of course: The remainder are the most interesting sources!
E.g. z > 3 galaxy populations

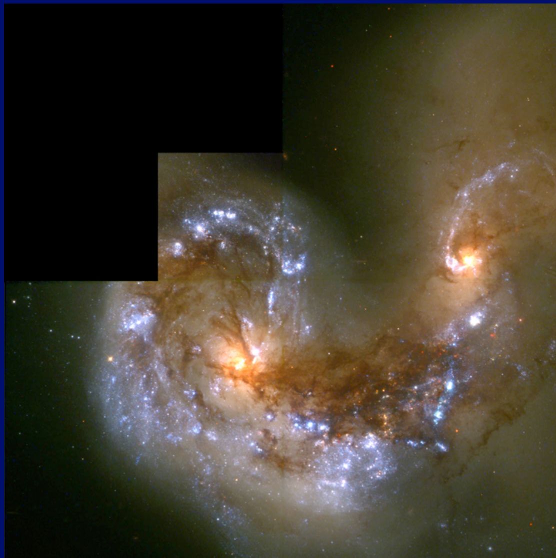
Resolving the extragalactic background spectrum

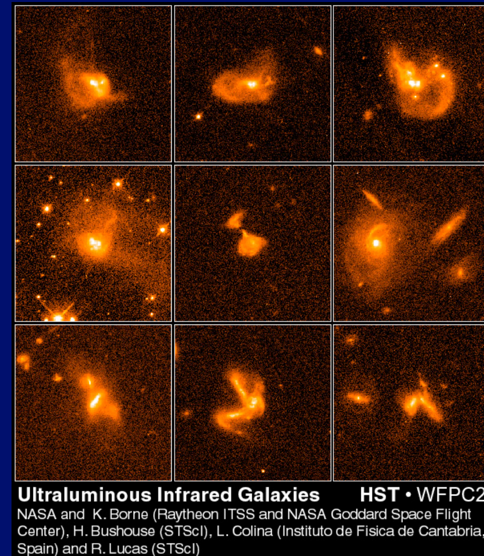


(i) ULIRGS/HyLIRGS typically have about ~10^{10} solar masses in stars

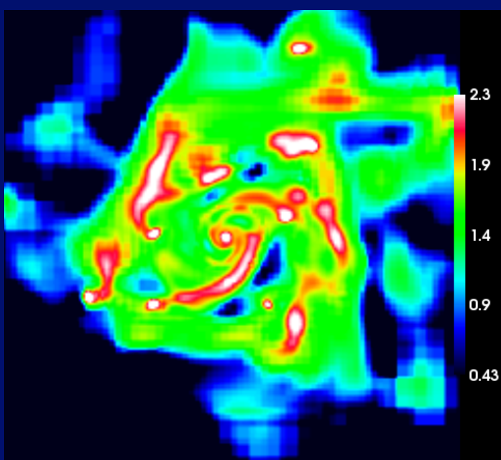
(ii) So the time scale for star-formation is [M*/(dM*/dt)] ~ 5 to 100 Million years (star-bursting galaxies!)

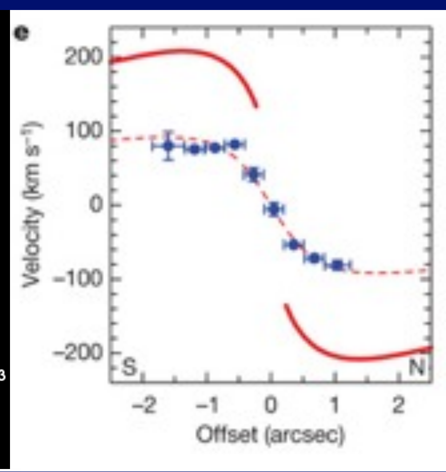
What kind of galaxies did we detect with Herschel?





In the local Universe ~100% of starbursts are driven by gas-rich galaxy mergers.





But at z ~ 1 to 2, observations show that some starburst galaxies are simple disks.

Is there a different mechanism to trigger a starburst at high redshifts?
(theorists: cold accretion mode)

Tacconi, L. J. et al. 2008, ApJ, 680, 246
Dekel, A. et al. 2009, ApJ, 703, 785

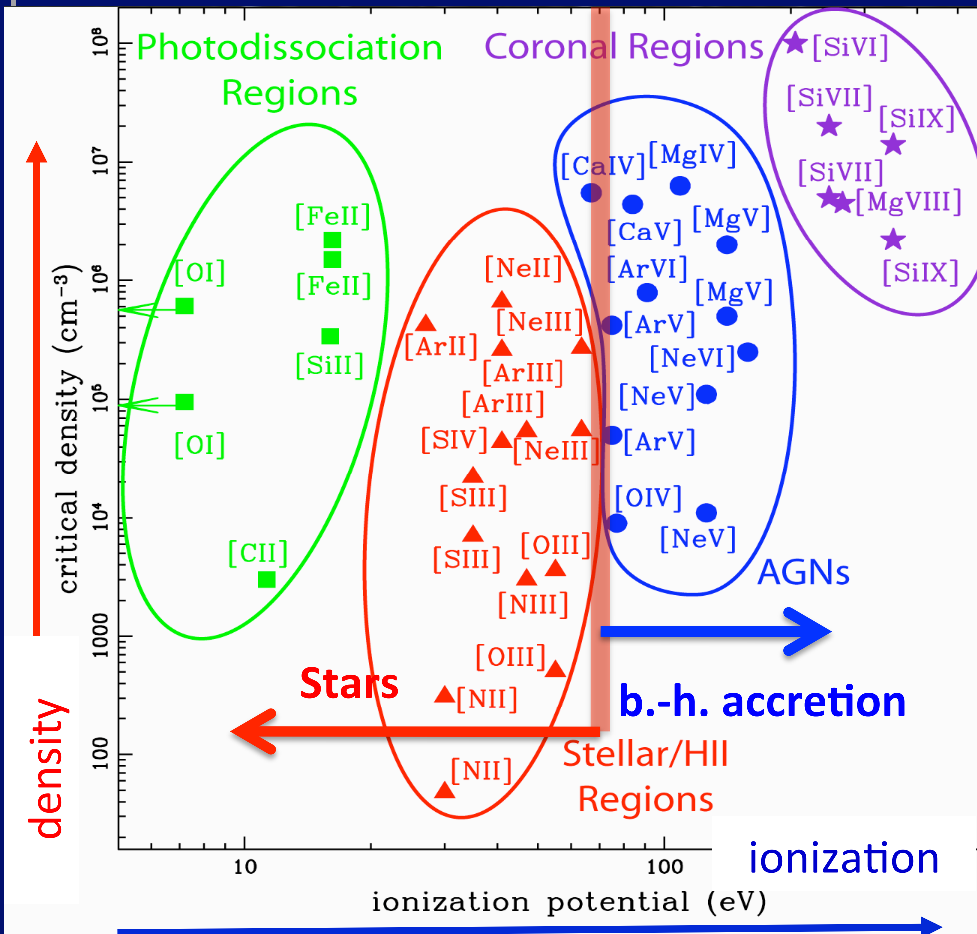
(a) What fraction of starbursts are mergers vs. cold flows?

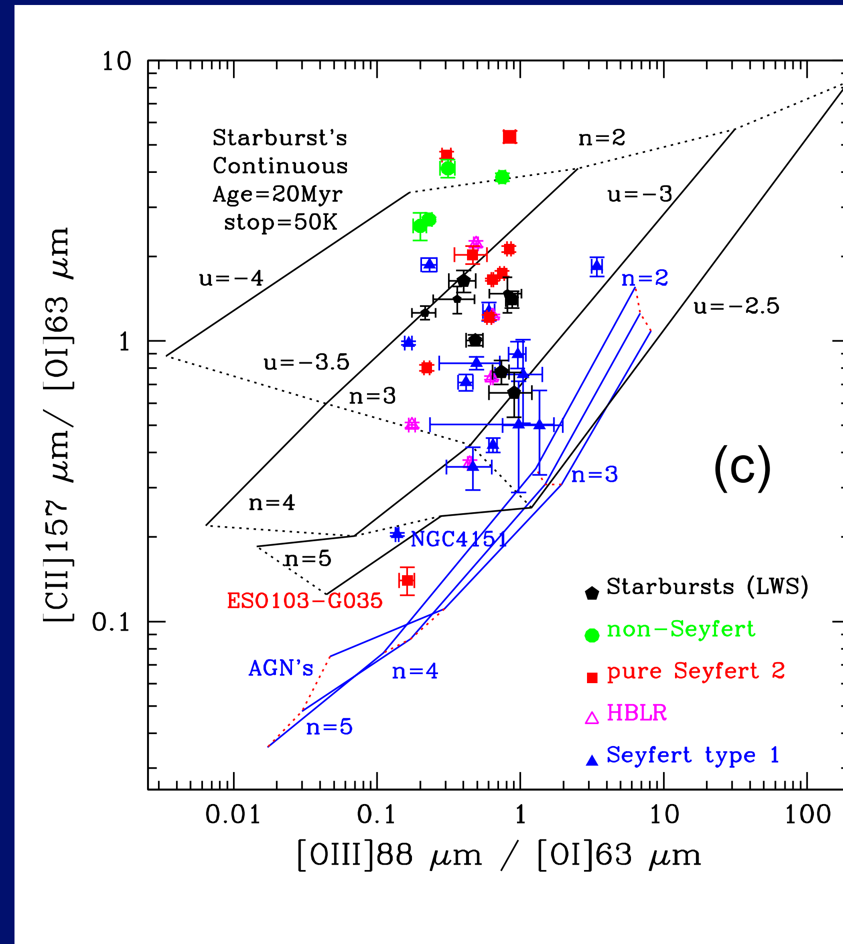
(b) Do the mergers evolve differently from cold flows? what stops the starburst?

What are Dusty Star Forming Galaxies (DSFGs)?

LOCAL ULIRGS REVIEW: SANDERS, D. AND MIRABEL, I. 1996, ARAA, 34, 749

Spinoglio et al.

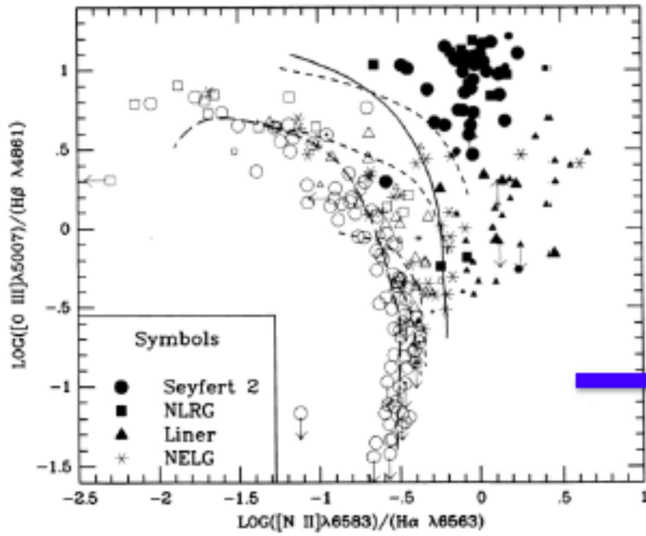




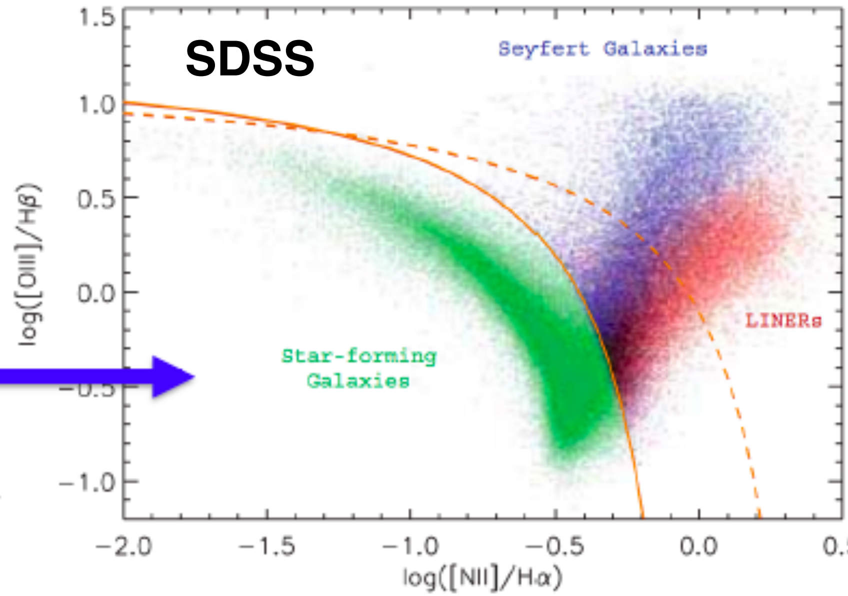
Far-IR rich in spectral lines

OPTICAL SPECTROSCOPY

Veilleux & Osterbrock **1987** (~100 galaxies)

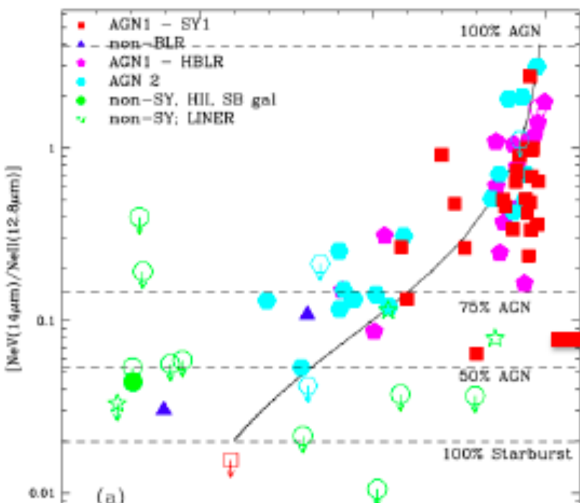


Groves+ **2006** (>10⁵ galaxies)



MIR-FIR SPECTROSCOPY

Tommasin+ **2010** (~60 galaxies)

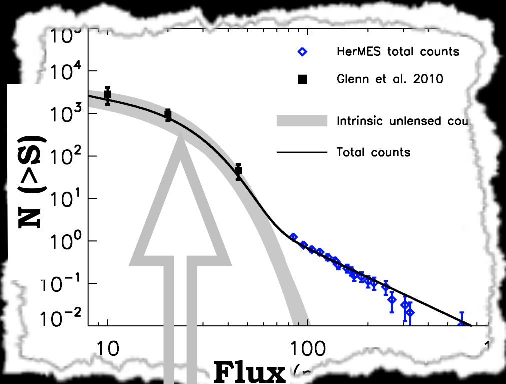


SPICA ~ 10^3 galaxies (but limited z range)

Far-IR Surveyor ~ 10^6 galaxies?

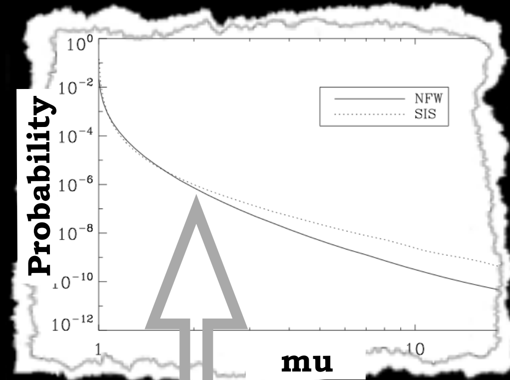
[slide adapted from Matt Malkan]

Far-IR rich in spectral lines



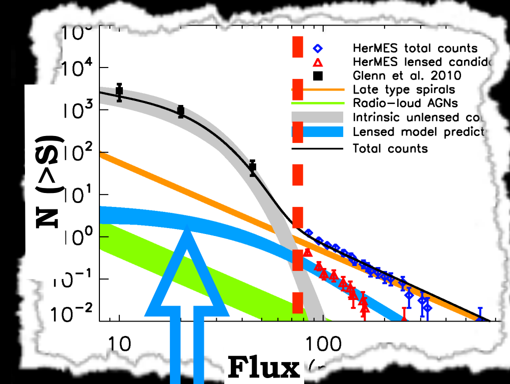
Intrinsic Source Count

$\otimes$



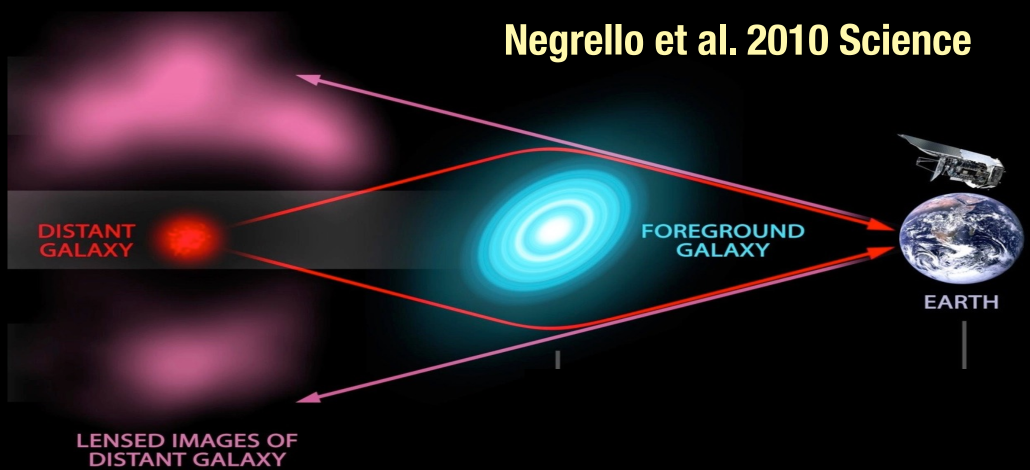
Magnification Cross Section

=



Lensed Source Count

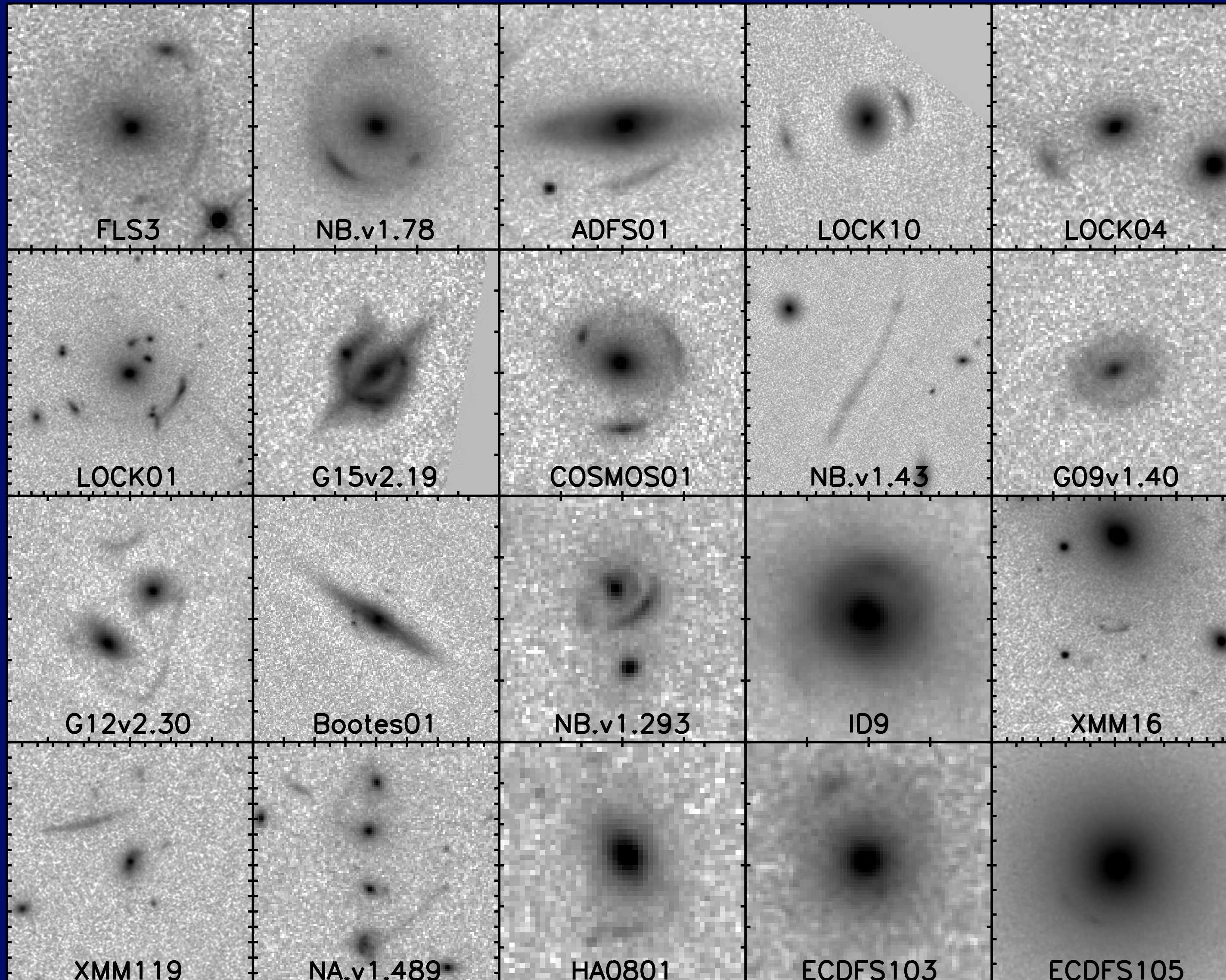
Negrello et al. 2010 Science



Julie Wardlow et al. 2013, ApJ
(UCI ex-postdoc)

<u>Lensing galaxy selection at sub-mm wavelengths > 95% efficient</u>

The Nature of Brightest high-z Herschel Galaxies

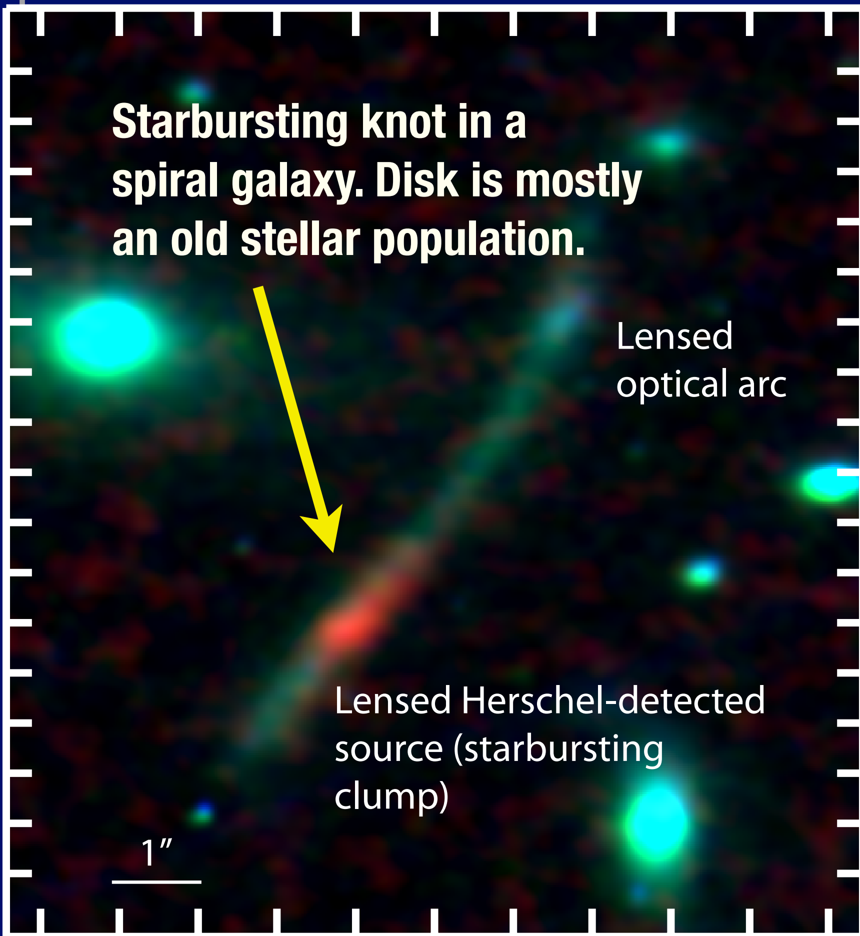


Jae Calanog
UCI PhD 2014

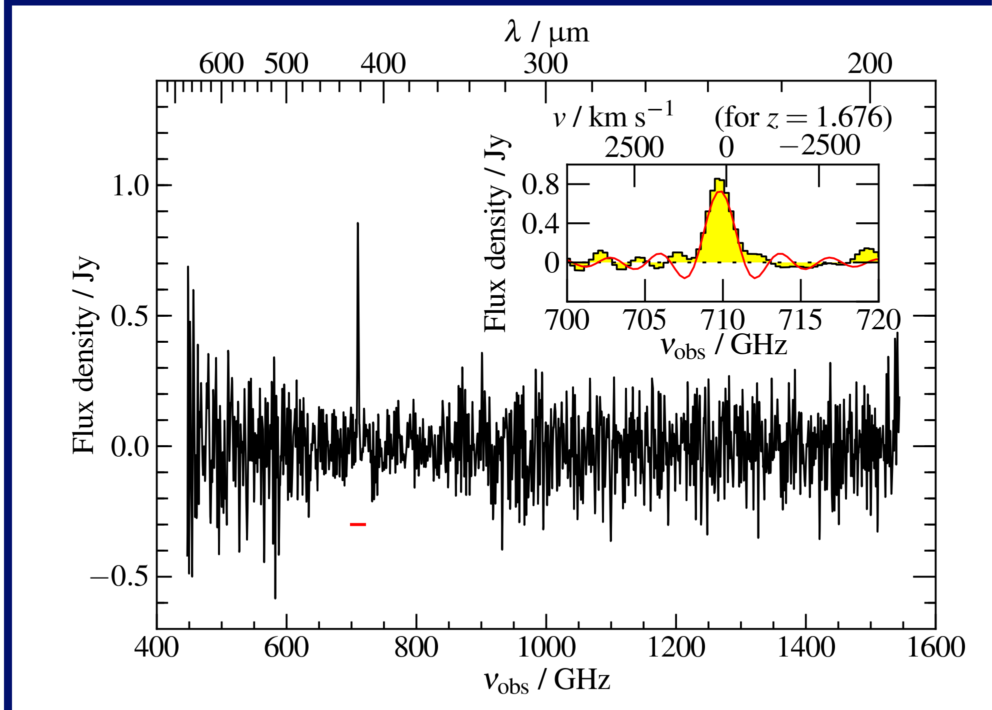
We now have 60 images like these in total with Keck/LGS AO

Keck LGS-AO Imaging

Fu et al. 2012; Bussmann et al. 2012; Fu et al. 2013; Calanog et al. 2014; Timmons et al. 2015



H-ATLAS: 650 sq. degrees. ~2 lensed Planck CSC sources. One in HerMES over 370 sq. degrees.

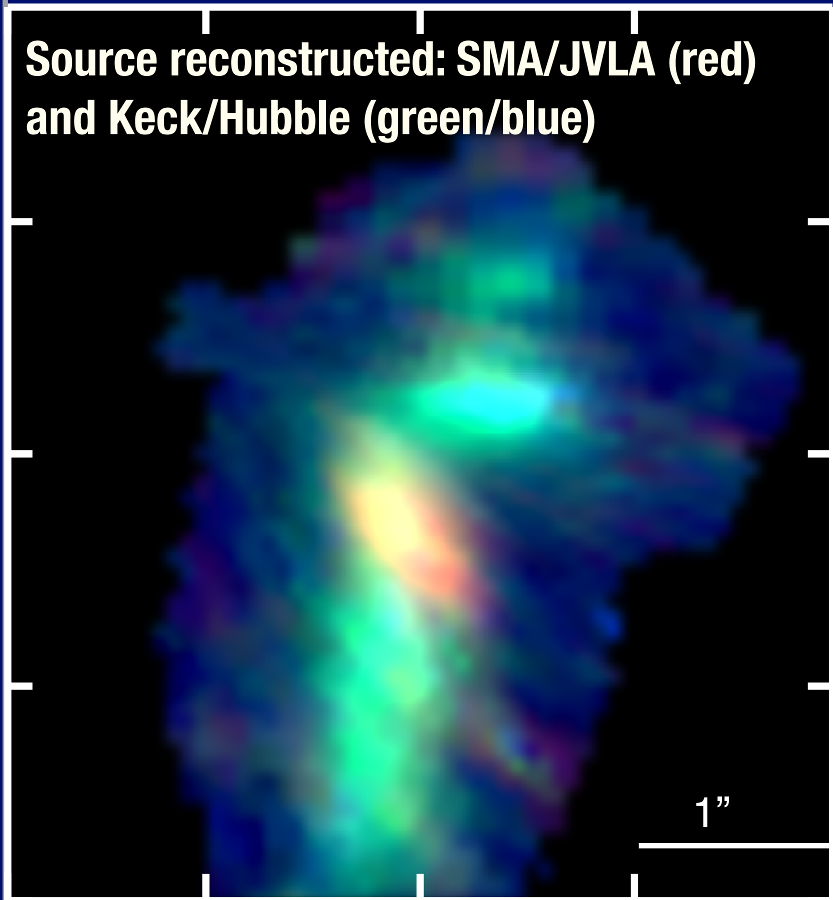


z=1.68, z determined from the Herschel-SPIRE/FTS spectrum with the 158 micron CII line

George et al. 2014; Timmons et al. 2015

Nick Timmons
UCI PhD 2017

Herschel Lensed Sources



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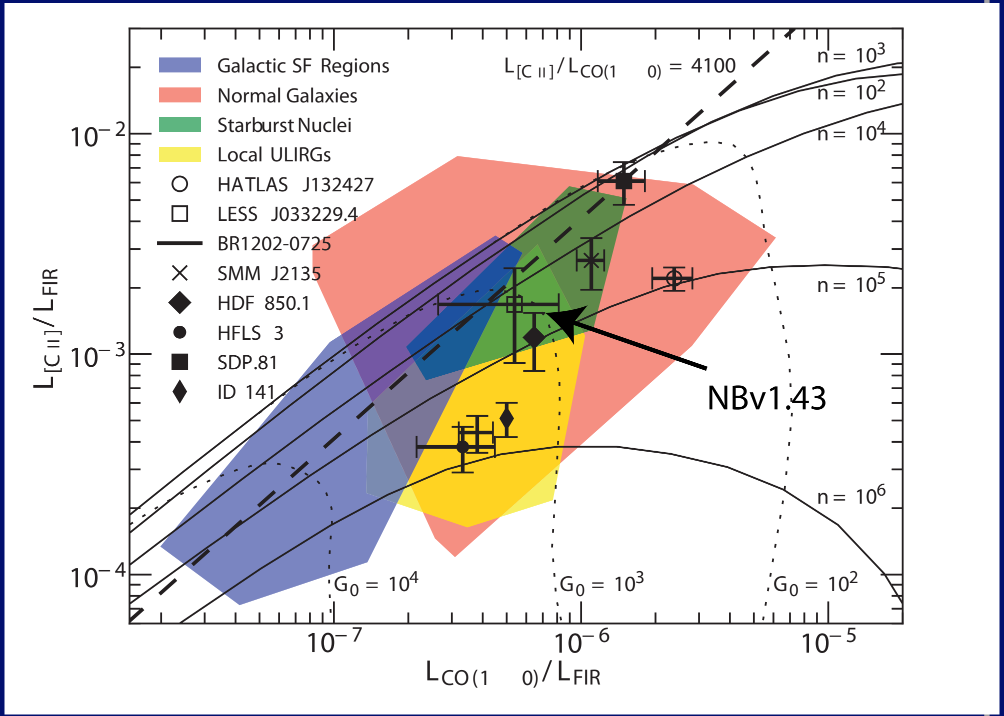

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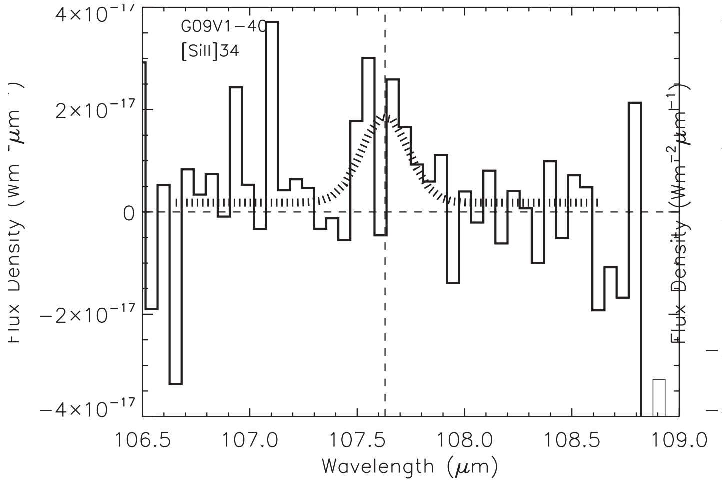
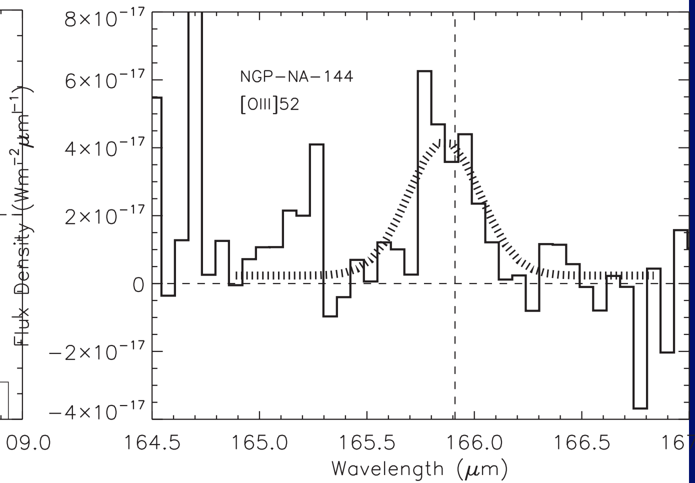
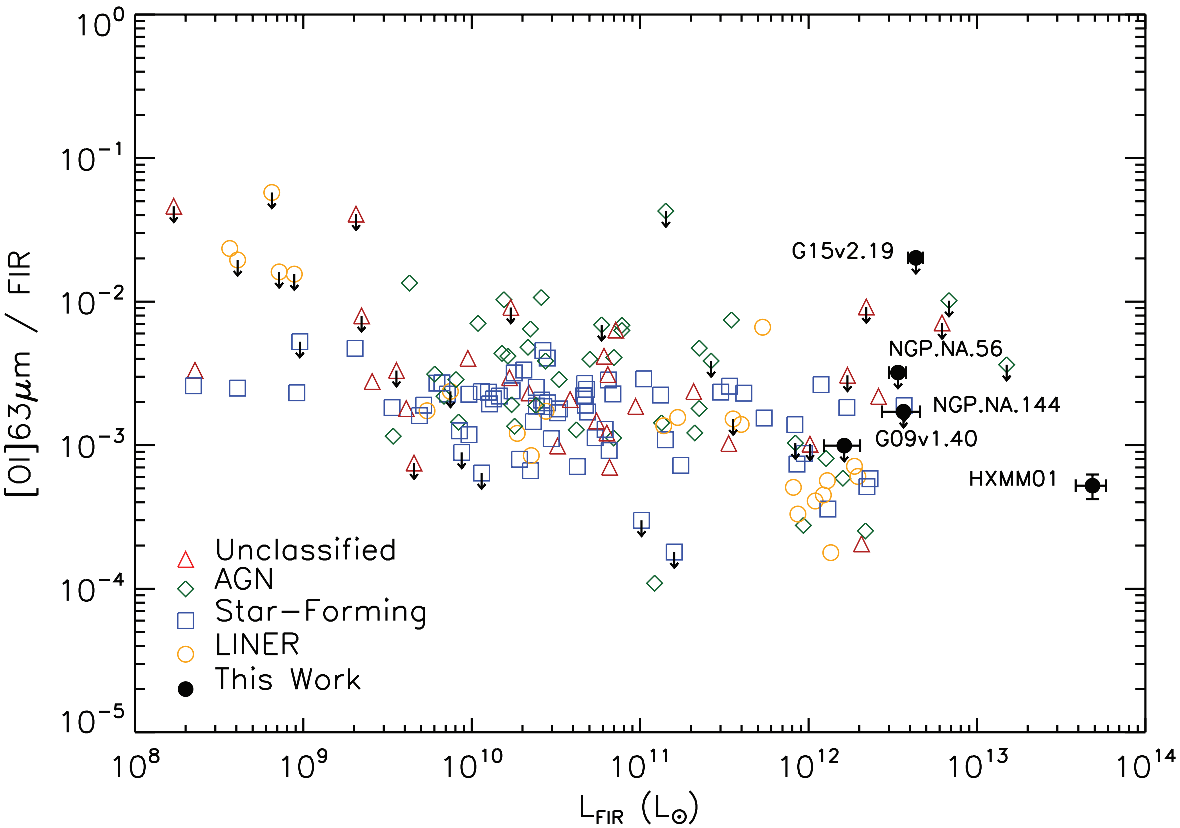
Herschel Lensed Sources







PACS spectroscopy of z > 1 galaxies

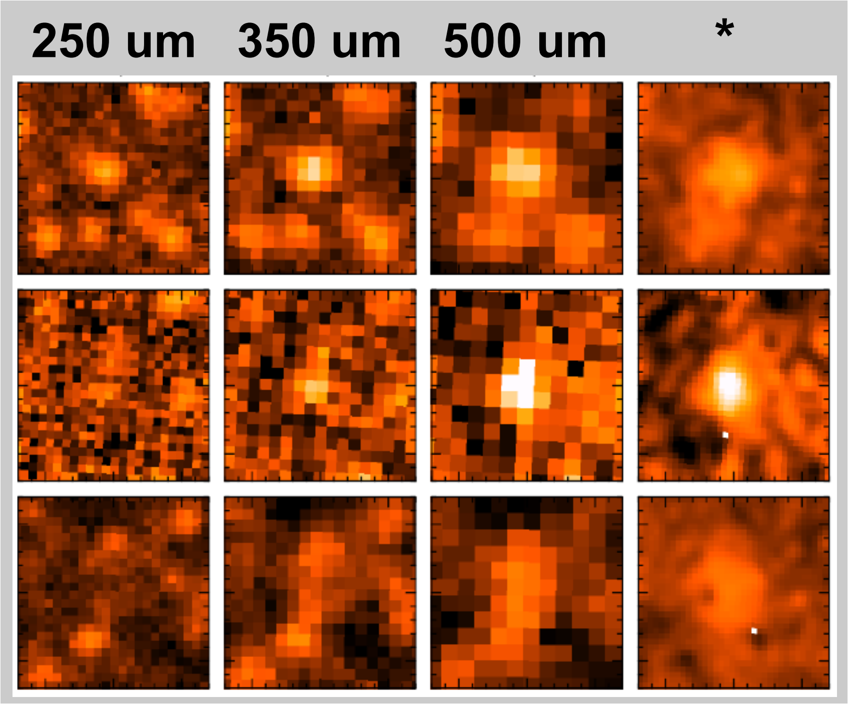
- **mainly lensed galaxies**
- **about 50 targets**
- **Mostly undetected**
- **detections are at best 3 to 5 sigma**

70 to 500 micron spectroscopy was not easy with Herschel - tons of upper limits over close to 500 hours unpublished.

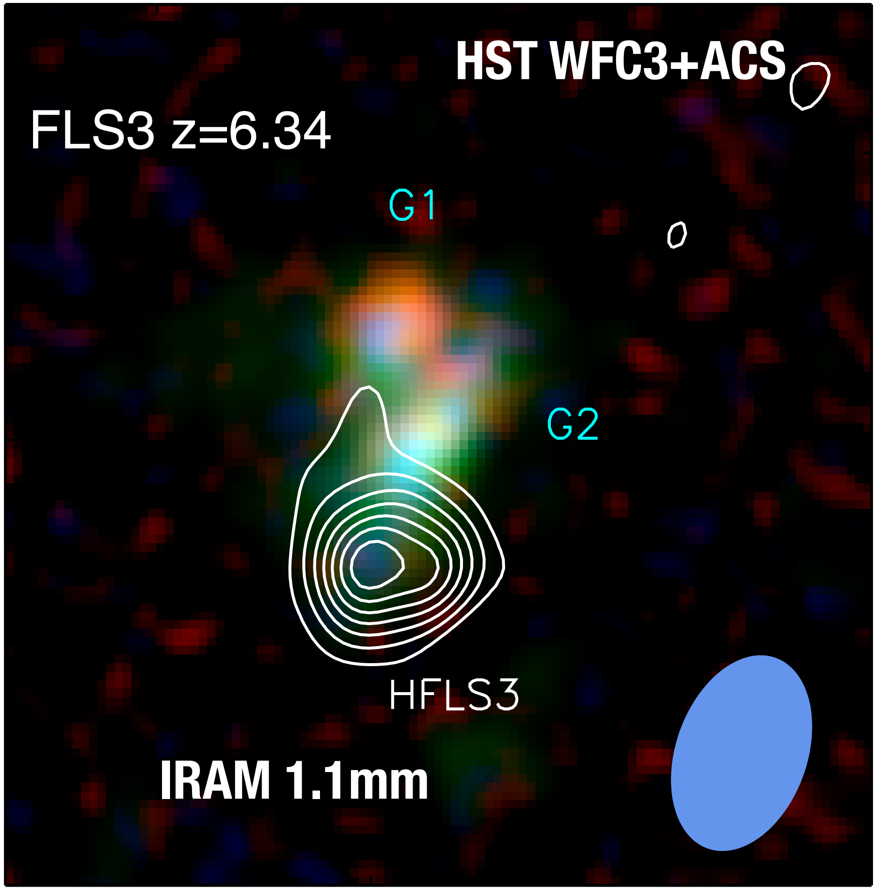
Wardlow et al. in prep

500 um peaked sources $S_{250} < S_{350} < S_{500}$: z > 4?

*Confusion reduced S(500) – fS(250)

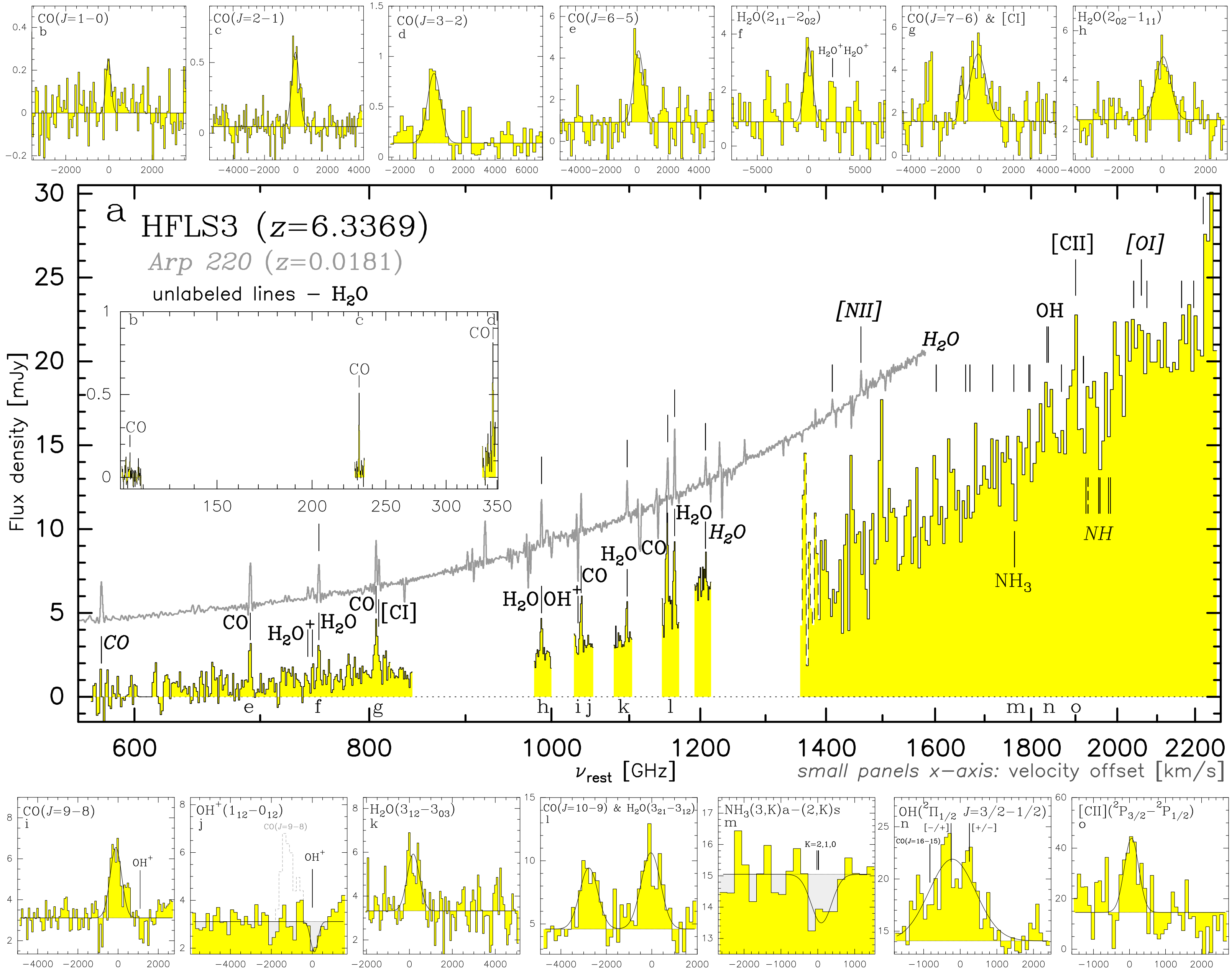


Dowell et al. 2014 ApJ technique

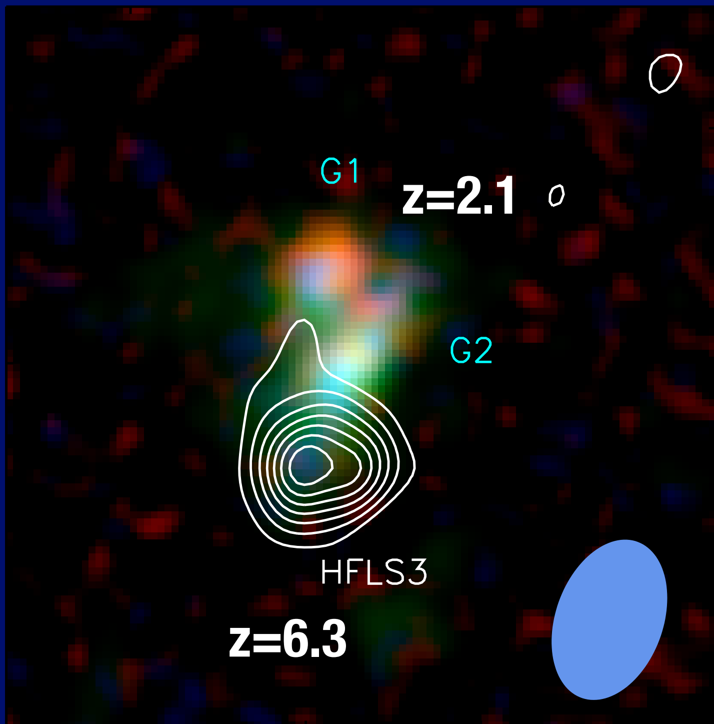


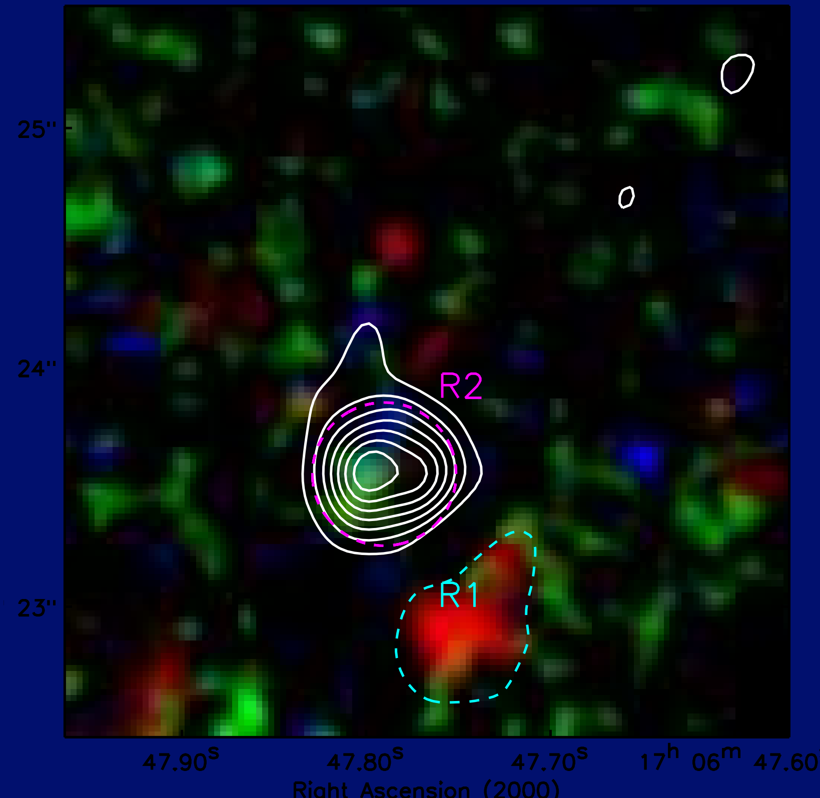
z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D. et al. Nature 2013; Cooray et al. 2014



a
HFLS3 (z=6.3369)
Arp 220 (z=0.0181)
unlabeled lines – H_2O
Flux density [mJy]
ν_{rest} [GHz]
small panels x-axis: velocity offset [km/s]
CO(J=1−0)
CO(J=2−1)
CO(J=3−2)
CO(J=6−5)
$H_2O(2_{11}-2_{02})$
CO(J=7−6) & [CI]
$H_2O(2_{02}-1_{11})$
CO(J=9−8)
$OH^+(1_{12}-0_{12})$
$H_2O(3_{12}-3_{03})$
CO(J=10−9) & $H_2O(3_{21}-3_{12})$
NH_3(3,K)a−(2,K)s
$OH(^2\Pi_{1/2}$ J=3/2−1/2)
$[CII](^2P_{3/2}-^2P_{1/2})$
[CII]
[OI]
[NII]
OH
NH
NH_3





Weakly lensed by two z=2.1 galaxies with magnification 1.6 +/- 0.3

[G2 identification in R13 as K-band ID of FLS3 incorrect]

$L_{FIR} = 6X10^{12}\ L_\odot$

<u>SFR ~ 1300 $M_\odot$/yr</u>

$T_{DUST} = 55 \pm 10$ K

$M_{DUST} > 10^9\ M_\odot$

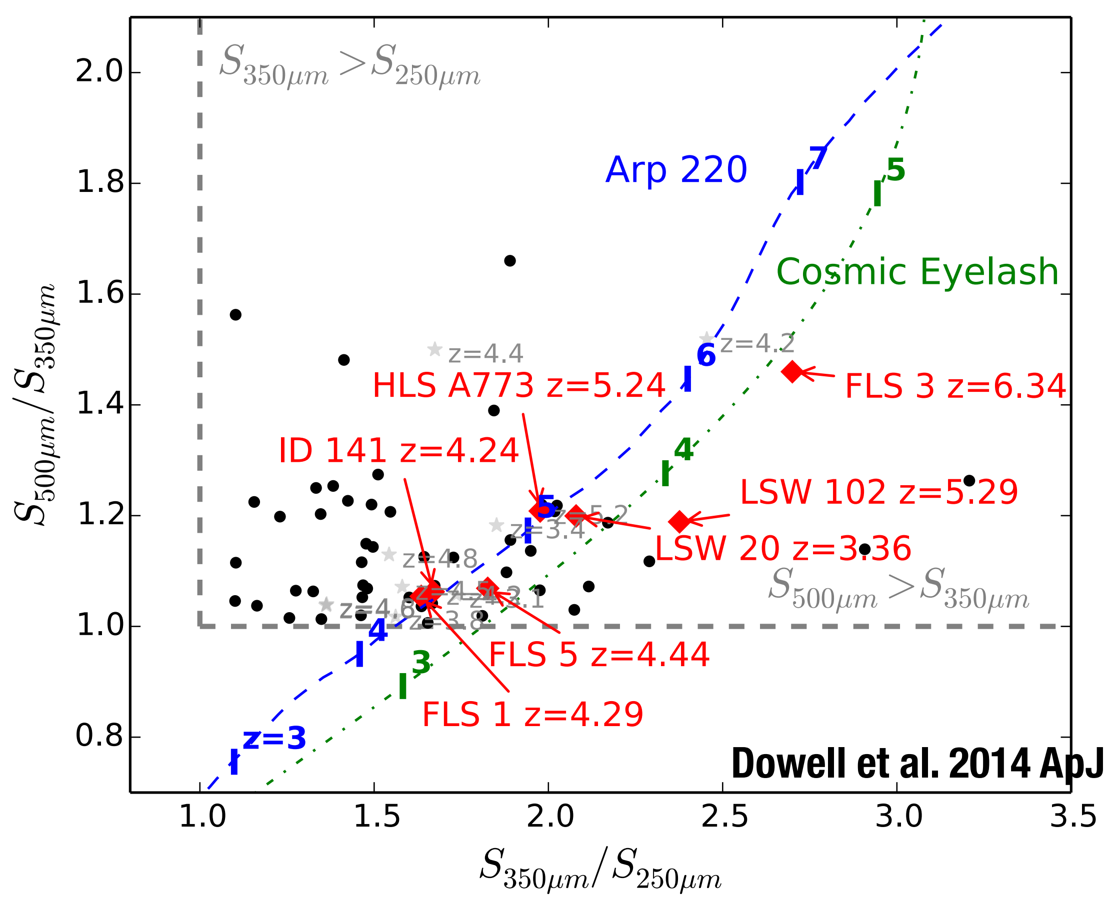
$M_{STARS} \sim 5X10^{10}\ M_\odot$

$M_{GAS} \sim 10^{11}\ M_\odot$

No evidence for a quasar/massive AGN!

z = 6.34 Dusty Starburst Galaxy in HerMES

Riechers, D. et al. Nature 2013; Cooray et al. 2014



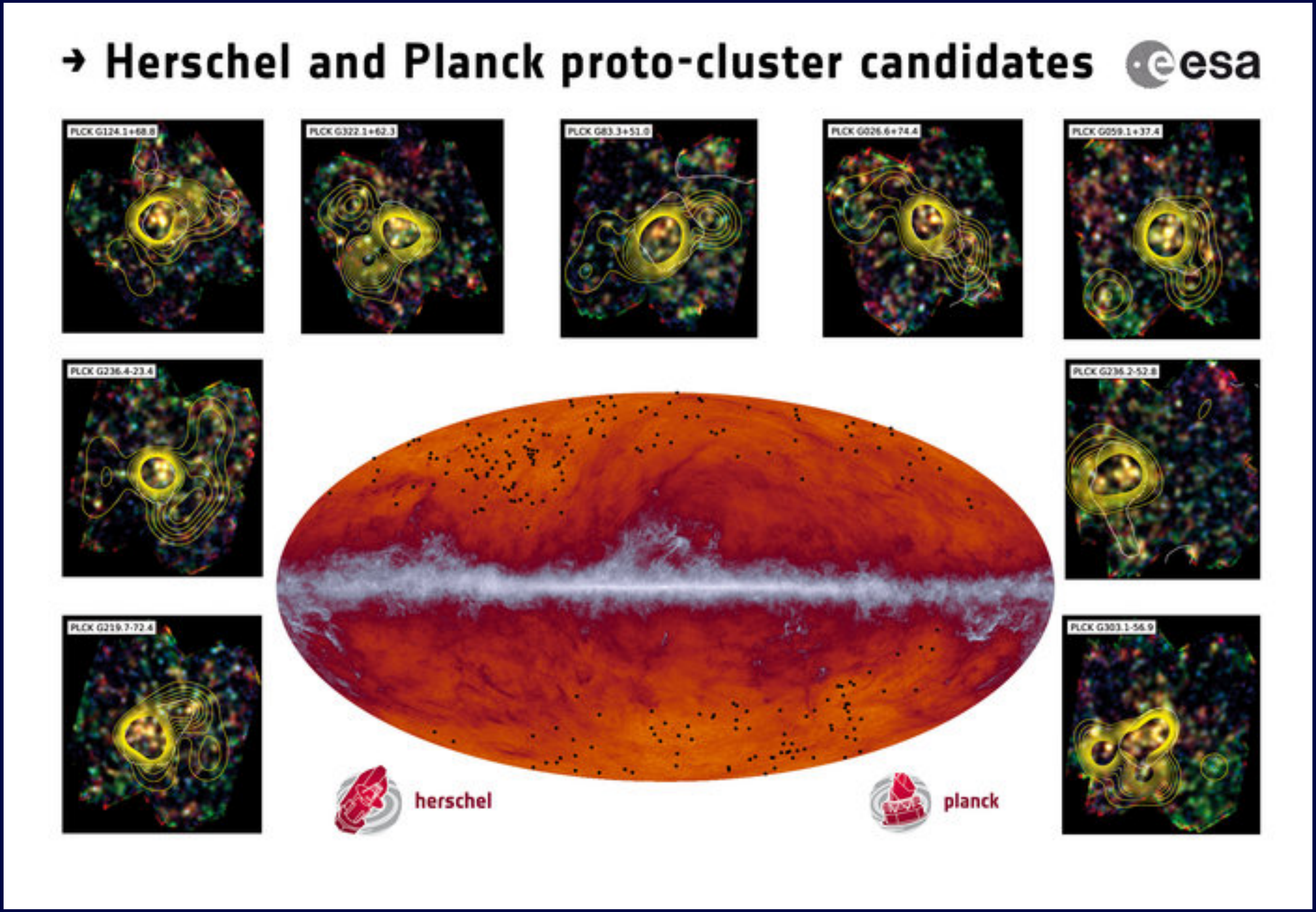
z > 6 galaxies can be discovered with just 100 to 600 micron coverage.

Need a survey area of around 1000 deg2 for statistically interesting number of targets.

[How angular resolution improvement with CALISTO increases or enhances identification of z > 5 galaxies with far-IR alone?]

"red" galaxies in Herschel

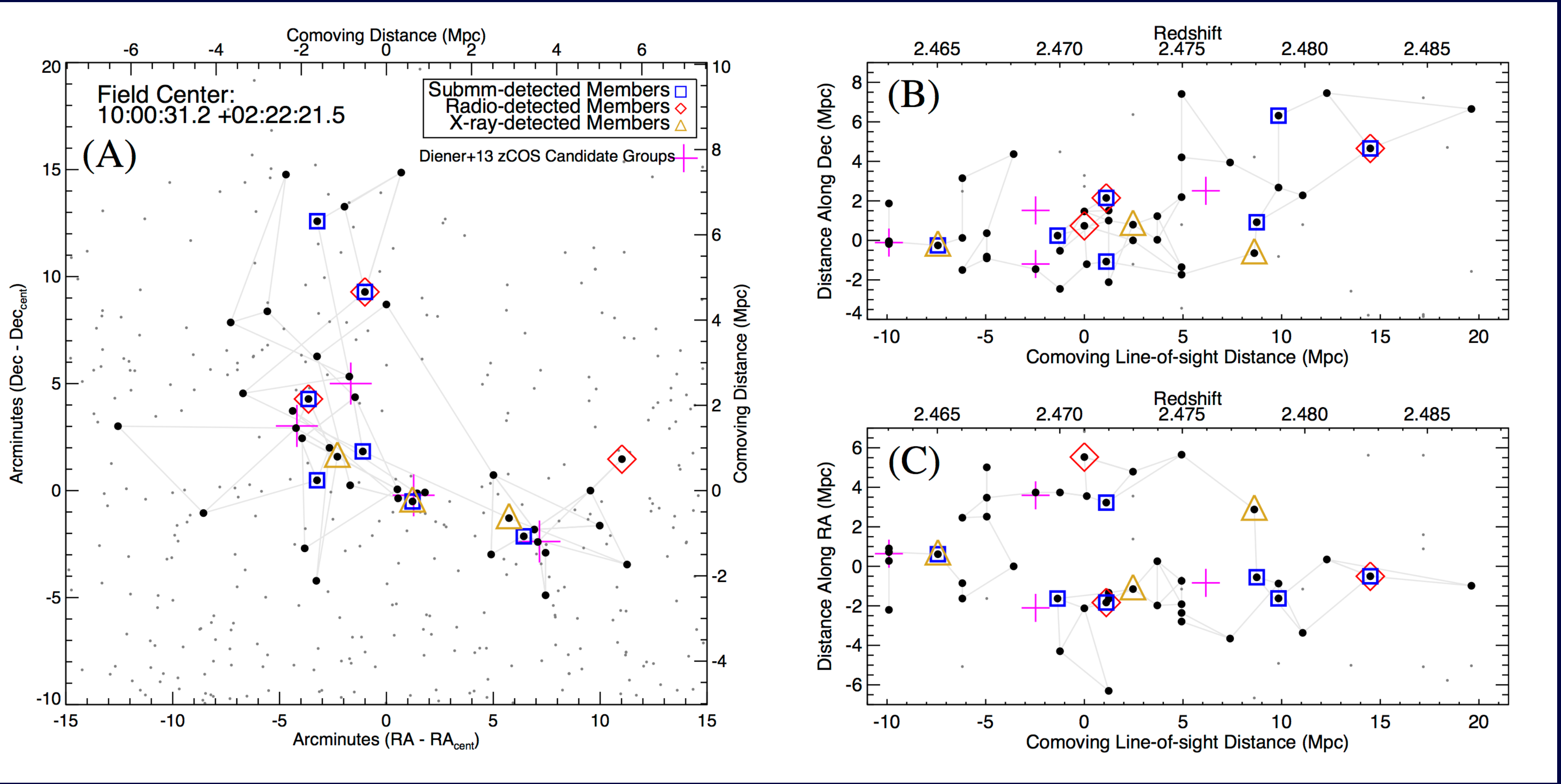
Galaxy proto-clusters at z >2
(before clusters “virialized” and bright in X-rays and SZ)



Galaxy proto-clusters at z >2

Casey et al. 2015: Herschel/SCUBA-2 + redshifts from Keck/ MOSFIRE

z=2.47, 8 dusty, starbursting galaxies and 40+ Lyman-break galaxies + radio + AGNs



Far-IR Surveyor over 1000 deg2 will find many 100s of these things - no follow-up as automatic redshifts

Intensity Mapping

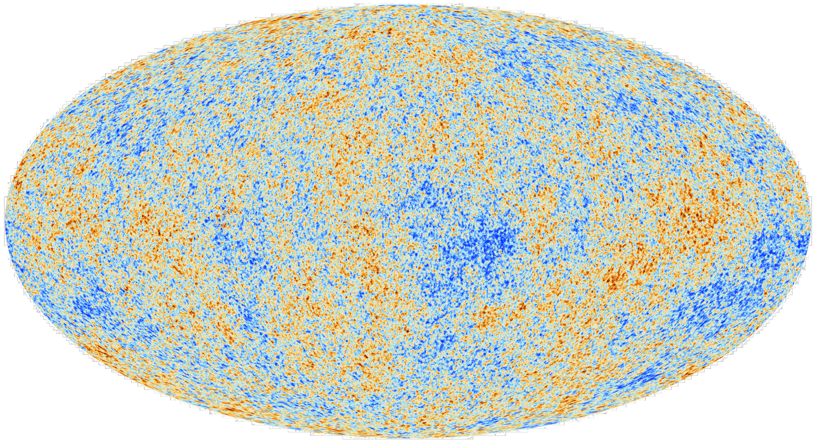
1. Individual sources are difficult to detect (sources are intrinsically faint, large instrument beam, etc),

2. We are interested in the total power from all sources, or

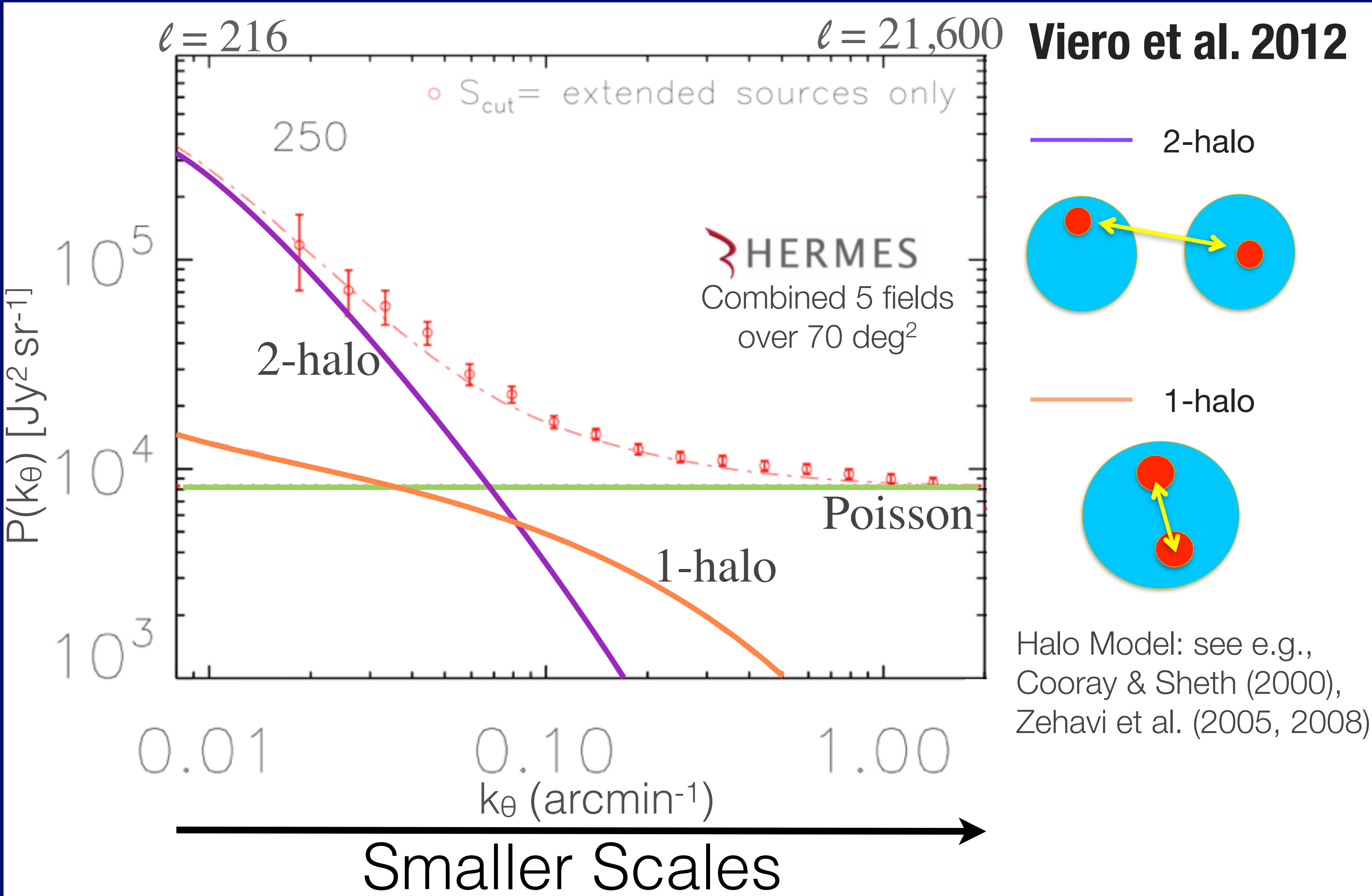
3. There is truly diffuse emission,

Science Applications:

- Galaxy Evolution
- Dark Matter and Galaxy Formation
- Epoch of Reionization
- Baryon Acoustic Oscillations.



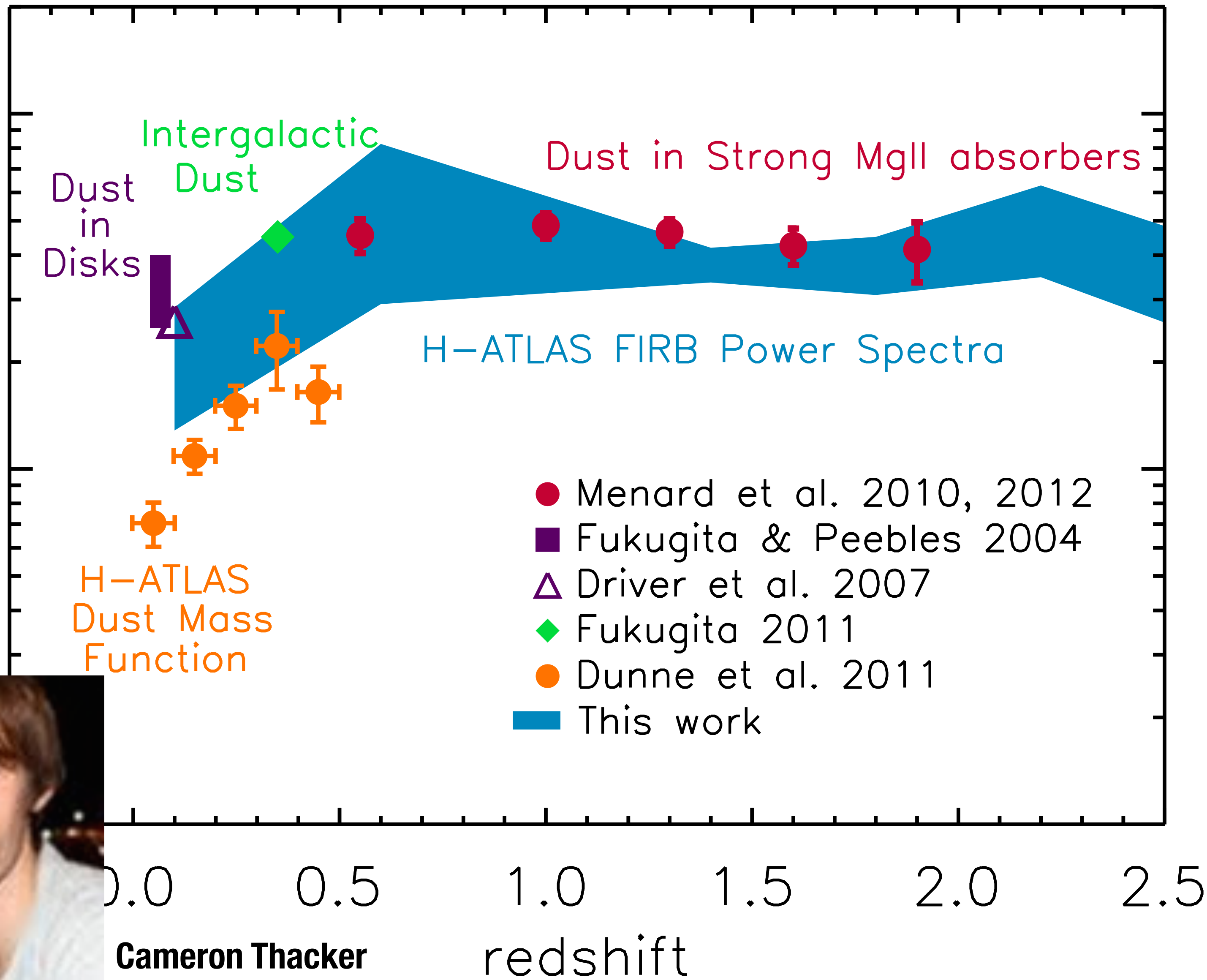
CMB is the canonical example of IM (Planck Collaboration 2013).



Cosmic Infrared Background Fluctuations with SPIRE

Viero et al. 2012; Thacker et al. 2013

Cosmic Infrared Background Fluctuations = Dust Content

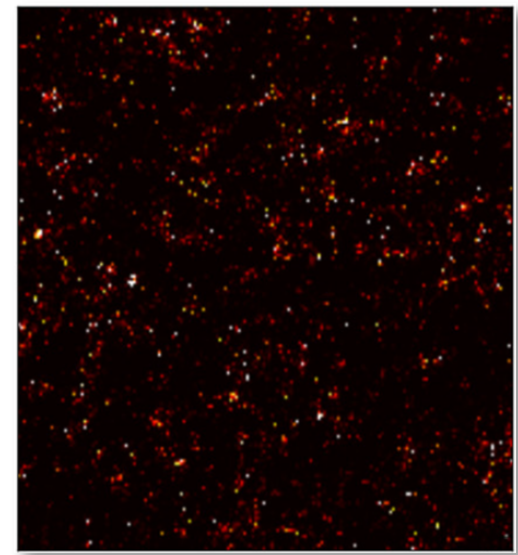


Cameron Thacker
UCI PhD 2015

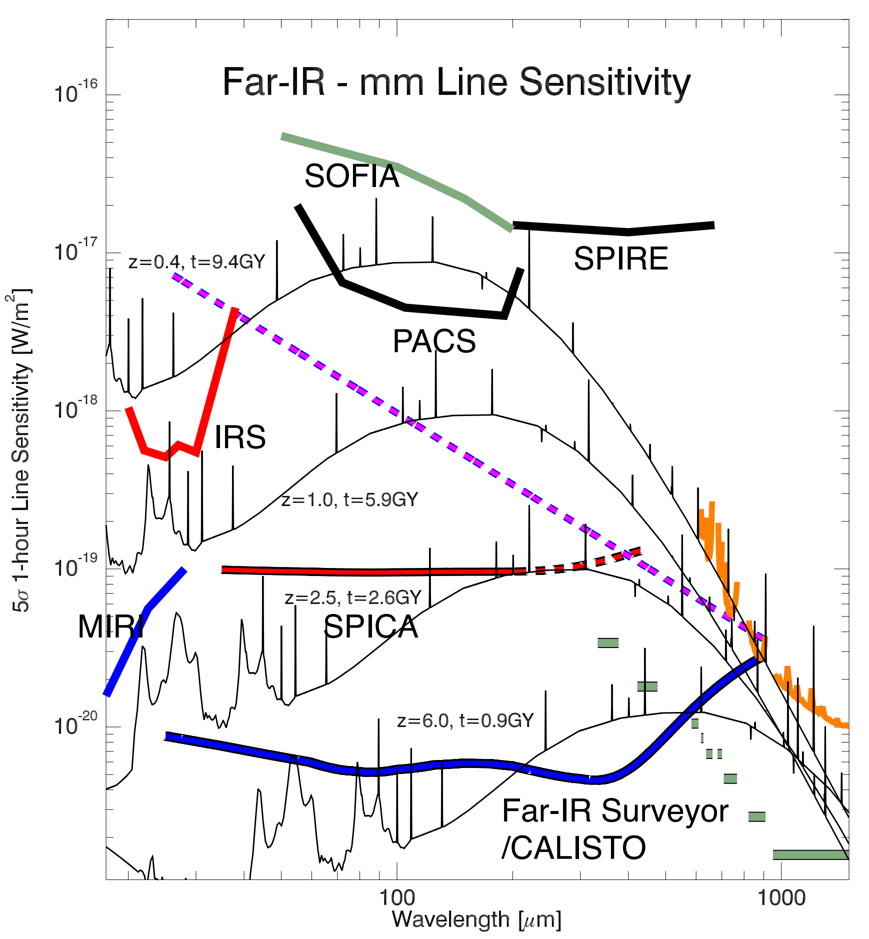
3-D Intensity Mapping

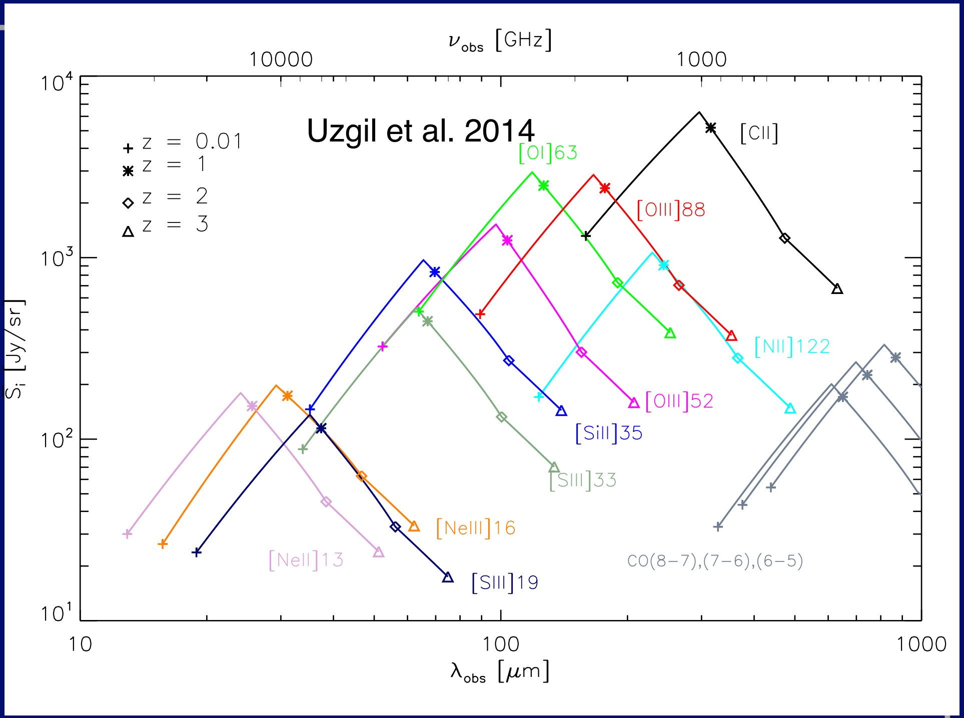
Sky map at z

Intensity map at z



- No need to resolve individual source
- Measure the collective emission from many sources
- Map large volume and faint sources at high z economically
- Astrophysical and cosmological applications from structure formation to measurement of SFRD of the universe at z > 2





For a concept Far-IR Surveyor between 60 to 650 microns:

[CII] at z = 0 and 3

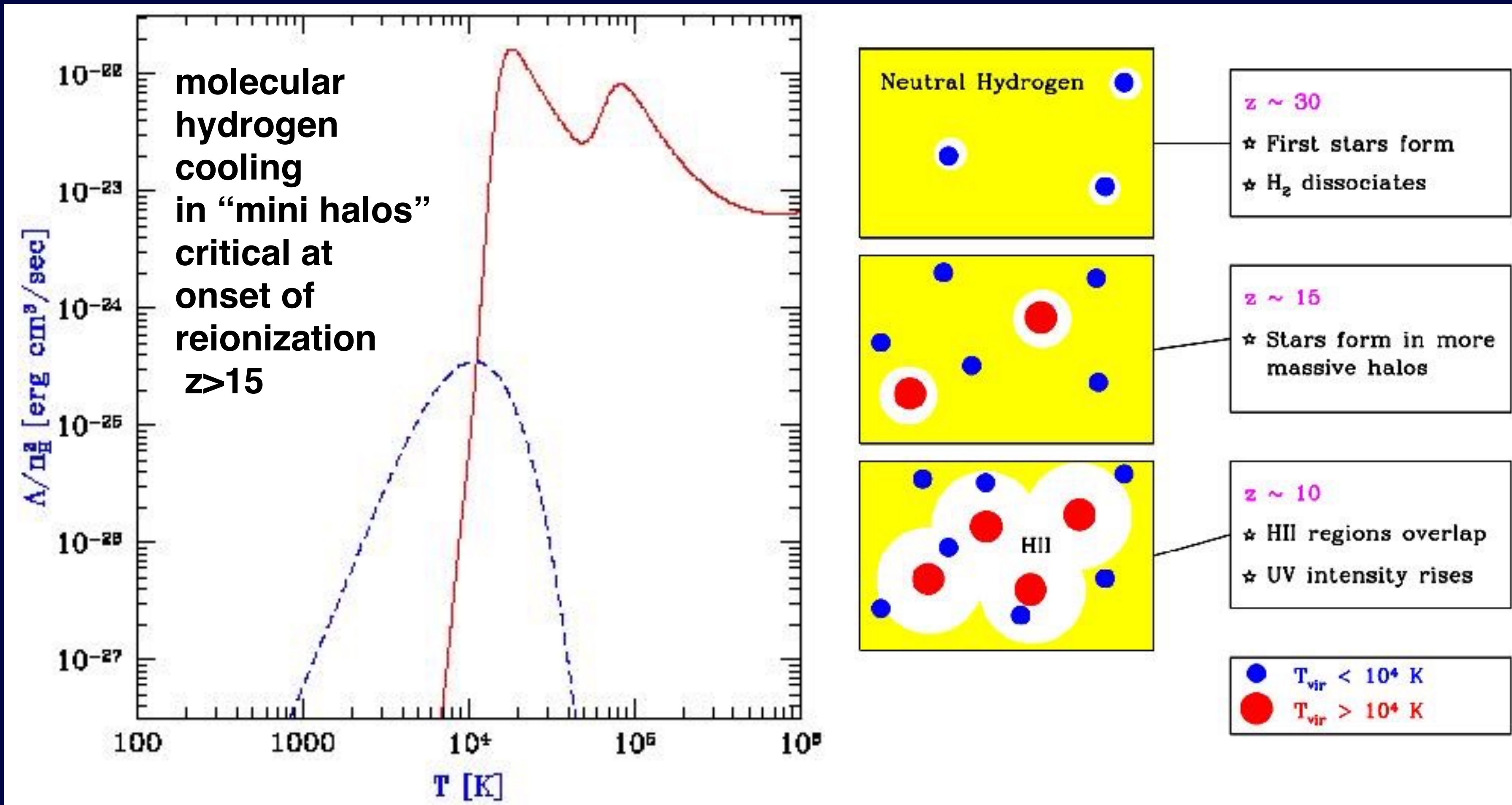
[OI] at z = 1 and 7 - extend to reionization

[OIII] … etc

intensity mapping signal-to-noise ratios in excess of 100 in redshift intervals of 0.3 around z of 2-3

3D intensity mapping with Far-IR Surveyor

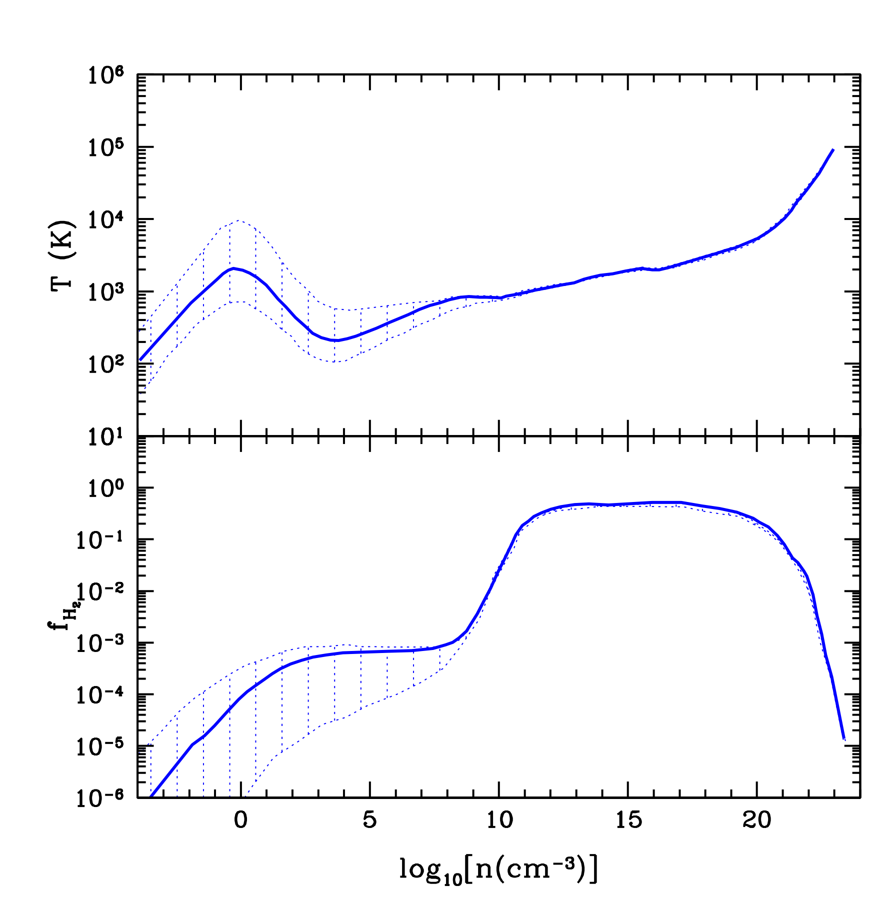
Molecular Hydrogen tracing primordial cooling sites/halos

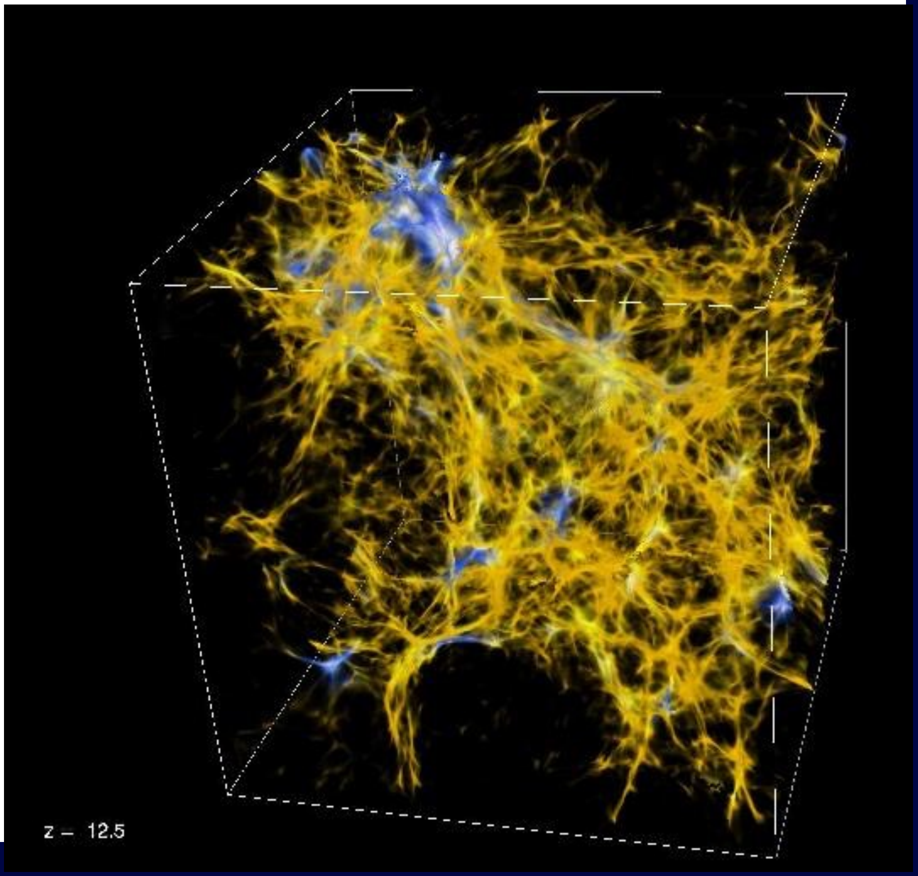


Outstanding problems at z > 6: billion to ten billion solar mass black-holes in SDSS quasars, Universe at < 600 Myr.
One solution is massive PopIII clusters collapsing - seed blackholes.
Need formation in minihalos at z > 15.

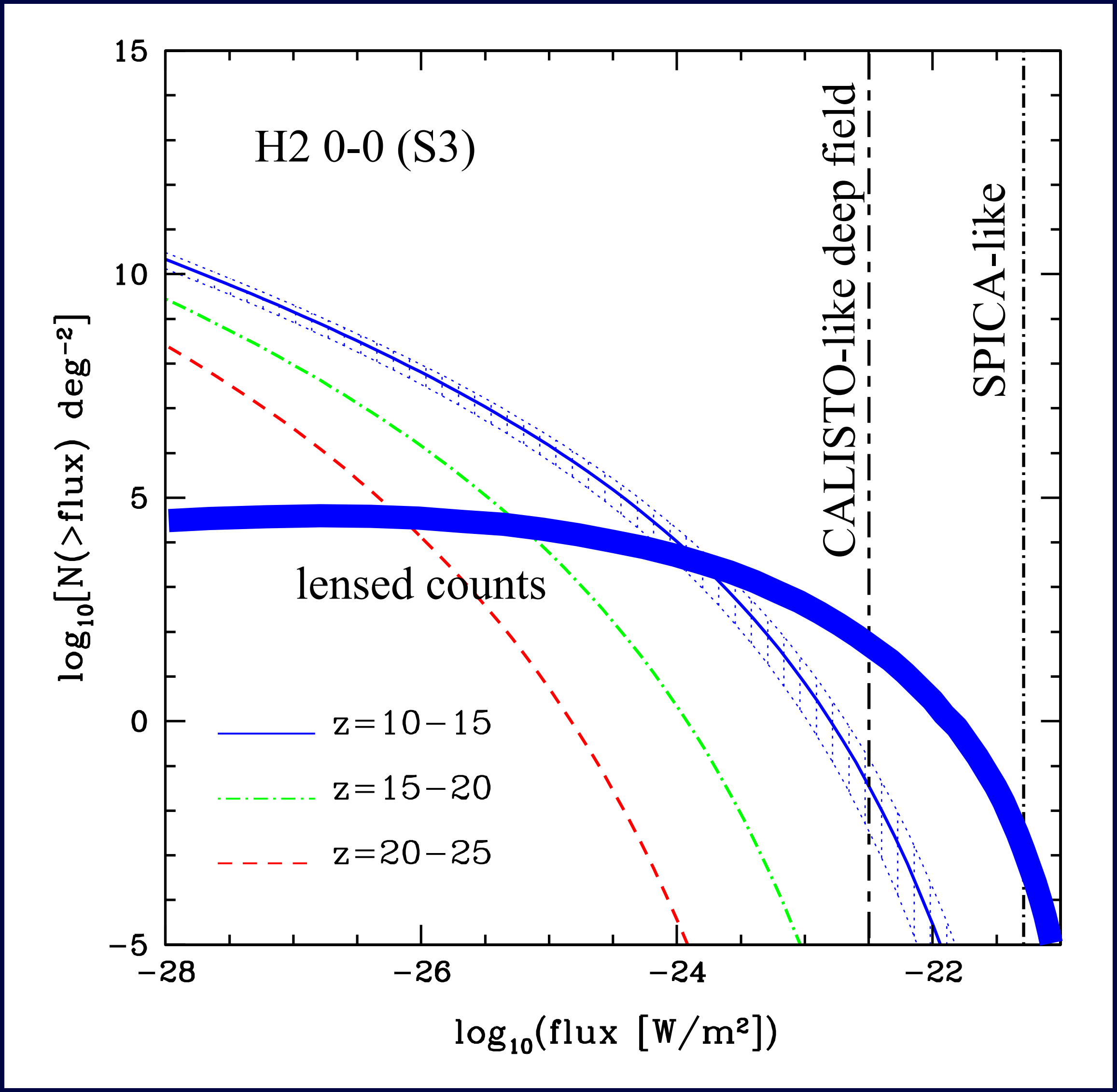
Molecular Hydrogen tracing primordial cooling sites/halos

Gong et al. 2012, ApJ
arXiv:1212.2964





Molecular Hydrogen tracing primordial cooling sites/halos



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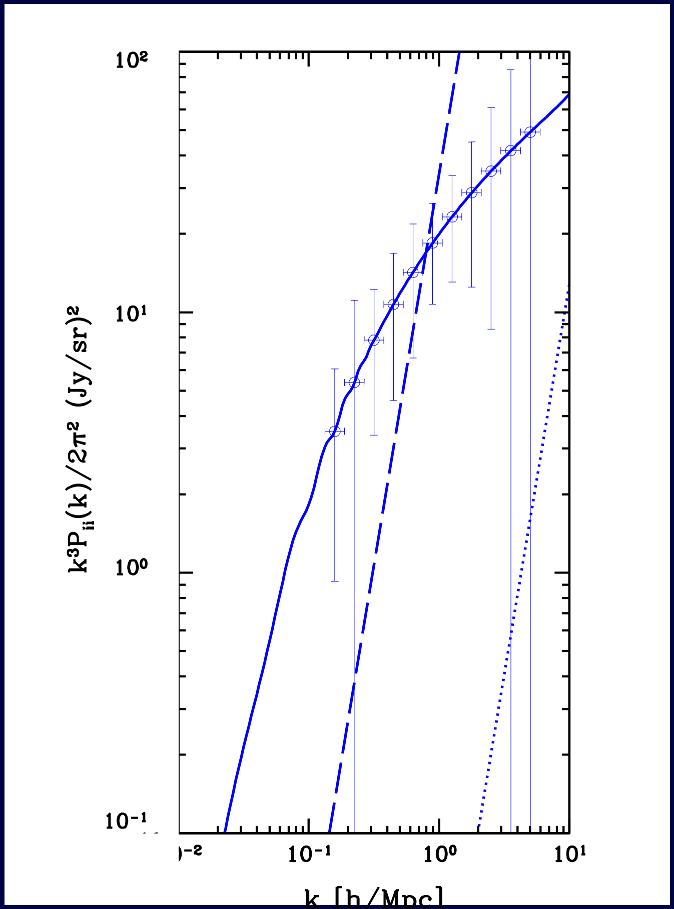

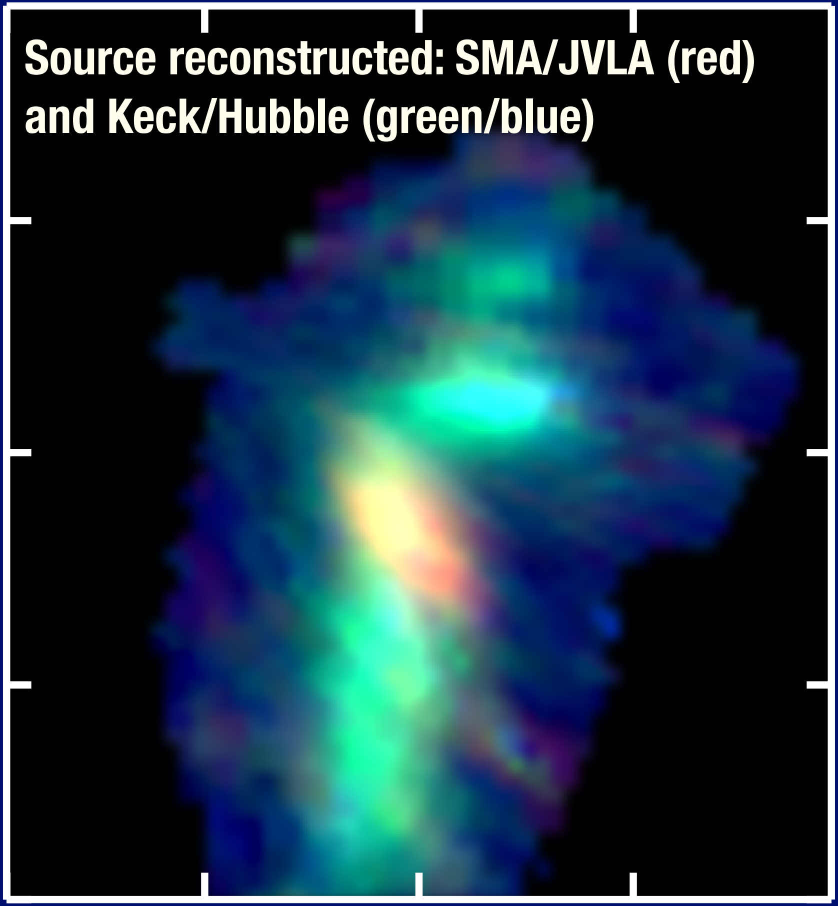

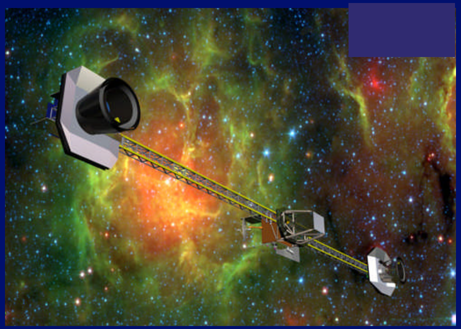

Interferometer should be able to resolve individual starbursting clumps out to z of 2.

Resolve narrow-line regions of local AGNs extended out to 500 pc in [OIV]/26 & [NeV]/24

Interferometer can also separate AGN from starburst components.

Sensitivity needed to lines at the level of 1e-19 W/m2.

Far-IR Interferometer Science Case

Wish list

single aperture: **Wedding cake survey from deep 1-3 deg2, medium tier of 100-300 deg2, and shallow wide 1000-2000 deg2, 60-600 microns R~300-600, 12 arcsec spatial resolution at 250 um**

interferometer: **line sensitivity below 1e-19 W/m2, probe ~100 range of AGN and starburst galaxies**

New interesting sciences:

(a) **Molecular Hydrogen pre-reionization at z ~15 (especially in a deep survey of lensing galaxy clusters for example).**

(b) **OI at z > 6 to combine with mm-wave CII etc from ground and 21-cm experiments such as SKA low-frequency**

(c) **3D spectral line intensity fluctuations centered around z of 2-3**

Summary